

more attention, in large part because it became the focus of James Clerk Maxwell's (1868) mathematical analysis of control systems using differential equations. Watt's challenge was to maintain the steam engine at a constant speed despite the fact that the loads upon it varied (as, for instance, different sewing machines attached to it in a textile factory would come on and off line). His solution was to attach a spindle to the drive shaft and then attach moveable arms to the spindle (see Figure 2.4). Centrifugal force would cause these arms to open up more the faster the engine was running. To these angle arms Watt attached a linkage mechanism that would reduce the opening of the steam valve the more the arms opened and increase the opening the more they dropped. Whenever the engine ran too fast, the arms would rise and that would cause the valve to close, slowing the engine down. Whenever it ran too slowly, the arms would drop, and that would cause the valve to open, speeding the engine up.

As technological systems developed for which control was critical, negative feedback came to be recognized as a powerful tool. It provided the foundational idea for the cybernetics movement,¹⁸ of which Norbert Wiener was a driving force. Wiener had interest and training in biology before earning his Ph.D. in mathematical logic and making important contributions to pure mathematics. Because he often collaborated with biologists, his inspiration for emphasizing cyclic organization probably lay as much in biology as in mathematics and engineering. During World War II he and Julian Bigelow took on the challenge of developing a control system for antiaircraft fire (the challenge stemmed from the fact that the airplane moves a considerable distance in the approximately one-minute interval that it takes a projectile to reach it). They recognized that the problem was not essentially different from the problem an animal faces in moving its limbs and were inspired to employ negative feedback. Thus, their strategy was to predict from radar information the future location of the plane but then correct the prediction based on the difference between the actual and predicted location at the next timestep. They found, however, that if the feedback signal was at all noisy and the system responded too quickly, feedback caused it to go into uncontrollable oscillations. Wiener and Bigelow consulted with Mexican physiologist Arturo Rosenblueth, who reported similar behavior in human patients with damage to the cerebellum. In both cases, they concluded, averaging techniques had to be invoked to dampen the response.

¹⁸ Indeed, Wiener was led to the term cybernetics while thinking about Watt's governor. Looking into the etymology of the word *governor*, Wiener followed the path to the Greek word for governor, *kybernan*, and encountered the Greek word *kybernetes*, steersman.